

DEVELOPING INTEGRATED TECHNICAL APPROACHES TO CHARACTERIZE ECOSYSTEM SUSTAINABILITY: WATERSHED, GROUND-WATER BASIN, AND WETLANDS PERSPECTIVES

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ABSTRACT

This paper presents the challenge, goals, and general approach for quantifying and measuring ecosystem sustainability, including human components, from a hydrologic system perspective. These integrated, multidisciplinary approaches and tools are used to identify the key environmental functions and structures (physical and hydrobiogeochemical) at the wetlands, watershed, and ground-water basin scale that can be applied in ecosystem characterization and socioeconomic analysis.

THE CHALLENGE: SUSTAINABILITY OF ECOSYSTEMS

Sustainability can be viewed philosophically and hierarchically as a complex interplay of the human and natural systems. The natural systems, of which humans are a part, can be viewed as the lithosphere providing the basic physical and chemical structure or body, the atmosphere and the hydrosphere providing the basic circulatory system of gases and fluids, and the ecosphere or biosphere being the living organisms that are sustained. The additional complexity of the human element in these spheres adds the challenge of characterizing the social, political, and economic systems as they relate to the environment.

In this context, global human populations are increasing rapidly, and there is an increased per capita human demand on the natural resources. As a result, there is decreased resource availability, and most ecosystems are being altered in their structure and function. Ultimately, the quality of life for humans is altered, and the real question becomes “is there decreased sustainability of the human population?” similar to what may have happened to the Anasazi cultures that once resided in the southwestern United States.

Human activity focuses around water resources (derived from predominantly surface water systems (simple watersheds), ground-water systems (regional or subregional aquifer systems), or a combination of the two (watersheds with significant ground-water input from either local, subregional, or regional systems). At one scale of analysis, the health and sustainability of an ecosystem, including human participation and welfare, may be evaluated from a watershed or ground-water basin perspective. This perspective includes the nature and mechanics of ground-water recharge, discharge, storage, and flow system dynamics, and surface water input, outflow, storage, and streamflow system dynamics. In addition, the non-human and human input to, and output from the chemical systems, including the source, transport, and fate

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of contaminants, and the flow of nutrients within the system, are important for the evaluation of sustainability.

At another scale, the connectivity of the surface water and ground-water system is observed through baseflow in streams, ground-water discharge zones forming wetlands, and riparian habitat. This connection is critical from both a water supply and water quality perspective in the realm of ecosystem, and therefore, human sustainability. In essence, the wetland is an indicator of ecosystem “health”, and the measure of wetland function changes can be a measure of sustainability trends within that system.

It is desirable, therefore, to approach the question of sustainability from both perspectives and scales in an integrated and linked fashion. Ideally, two perspectives may be offered based on the nature of the system being studied: 1) the watershed approach linked with ground-water and wetland subsystems; and 2) the ground-water basin approach linked with surface water and wetland subsystems. The watershed approach may be more applicable to regions of wetter climates and subsurface materials that are unfavorable for significant subsurface water resources (usually localized subsurface hydrological contributions). The ground-water basin approach may be more favorable to regions of semi-arid to arid climates and subsurface materials that are favorable for significant subsurface water resources (usually localized and variable surface hydrological contributions).

THE GOAL: DEVELOPING INTEGRATED TECHNICAL APPROACHES FOR SUSTAINABILITY MEASUREMENT

The goal, then, is to develop integrated technical approaches and tools to characterize ecosystem, and thus, human sustainability from the watershed, ground-water basin, and wetlands scales. These approaches will need to be stepwise, integrated, multidisciplinary, multi-scale, and multi-temporal hierarchical algorithms with nonlinear feedbacks. The general system components will consist of layers of information and processes integrated by Geographic Information Systems (GIS) or other data management and visualization tools, based on engineering, hydrogeologic, ecological, and socioeconomic principles. Water is a thread through all of these layers. The tools will range from lab, field, and computer analysis and modeling of environmental parameters, to integrated GIS and mathematical and analytical modeling of environmental systems. Ultimately, the approach and tools will facilitate hypothesis generation and testing, and will be used as a potential planning tool for most applications.

Multidisciplinary teams of scientists, engineers, and economists will be needed, and the structure of a team carefully thought out (see ASTM Standard Practice # 6235 for “Expedited Site Characterization of Vadose and Ground Water contamination at Hazardous Waste Contaminated Sites” as an example of approach and teams; ASTM Standard Guide # 5979 for “Conceptualization and Characterization of Ground-Water Flow Systems” as an example of approach).

THE APPROACH: THE HYDROLOGIC PERSPECTIVE

Hydrologic conditions, including water quantity and quality, are extremely important for the sustained development of both ecosystems and socioeconomic systems. The structure and function of hydrologic systems affect water availability, nutrient cycling and hazardous waste transport, which, in turn, affect ecosystem productivity, species composition and biological diversity. Completing a cycle, biotic components of an ecosystem actively alter the structure and function of hydrologic systems by affecting organic matter accumulation, chemical transformation rates of many water-quality processes and other hydrologic conditions. Similarly, availability of sufficient water of acceptable quality is critical in sustaining socioeconomic development. This linkage is both direct through the socioeconomic value of the water resource and indirect through values provided by the associated ecosystem. Again completing a cycle, it is widely recognized that socioeconomic management decisions have consequences in terms of waste generation and land-use change that have measurable effects on hydrologic systems and ecosystems at local, regional and global scales.

Effective management of ecosystems and socioeconomic systems requires an understanding of hydrologic system structure and function. However, hydrologic systems are complex. Many fundamental physical and chemical processes affecting hydrologic system structure and function are not well understood and are the focus of much research. Techniques for extending hydrologic understanding from the laboratory or point scale to scales of interest to ecologists, socioeconomic specialists, and hydrologic system managers are in need of being developed and applied. Reliable estimation of hydrologic conditions when confronted with hydrologic data limitations, including water quantity and quality data, remains a point of debate for both surface and ground-water hydrologists.

Comprehensive research integrating hydrology, ecology, and socioeconomic factors at the system scale is the vision contained in this paper. Acknowledging the complexity of hydrologic systems, past efforts have limited the scope of research by:

1. Considering only the surface water or ground water portion of the hydrological system,
2. Considering only selected biogeochemical processes within the hydrologic system,
3. Assuming arbitrary hydrological boundary conditions as a means of reducing the size or complexity of a study area,
4. Simplifying the description of aqueous chemistry or ignoring selected chemical components that are believed to be constant or unimportant to system response, or
5. Describing components of the hydrological system with empirical methods.

While our incomplete understanding forces researchers to accept a simplified description of complex hydrologic systems, the simplifying assumptions too frequently reflect subjective decisions based on the past experience and expertise of investigators with little understanding of or interaction with ecologists, socioeconomic specialists, and systems-scale hydrologists or hydrogeologists. In fact, the strength of the Conceptualization and Characterization (See ASTM Standard Guide #5979) and ESC (See ASTM Standard Practice #6235) approaches is that the “real site” data and the step-wise, integrated, hierarchical methods help to define the hydrologic system, and to reduce the uncertainty of systems analysis caused by the focused experience of the scientist or engineer.

There is a need for environmental systems research identifying the key environmental processes that must be understood if society is to make land use, hazardous waste and other related management decisions consistent with sustainable development. This research should:

1. Integrate the knowledge and current technical limitations of hydrologists, environmental chemists, ecologists, and socioeconomic specialists,
2. Include structural and functional descriptions of the key environmental processes suitable for management needs, and
3. Develop objective methods for process identification and description that avoid potentially arbitrary limiting assumptions.

The overall goals of our environmental systems research are:

- To identify the key environmental functions and structures (physical and hydrobiogeochemical) at the scale of hydrological systems (watersheds, wetlands, regional ground-water basins) that are needed to make socioeconomic and ecological management decisions, and
- To develop techniques for reliably and efficiently characterizing the functions and structures at the scale of these hydrologic systems.

Our research efforts are focused on a set of master environmental variables. By understanding the spatial and temporal structure of a set of master variables controlling system function, we believe that ecological, human health, and socioeconomic impacts of specific land and water use decisions can be determined in a reliable and efficient manner. The master environmental variables may include, but are not limited to:

Physical Hydrology

- Volumetric flow rates of water (Q)
- Flow paths
- Velocity or residence time
- Sediment concentration or load
- Hydrogeologic control on water movement and storage

Hydrobiogeochemistry

- Acidity (pH)
- Redox condition (Distribution of dominant electron acceptors)
- Chemical phase distribution (equilibrium constants, specific surface area)
- Surface and subsurface mineral and rock composition
- Microbial Activity

In addition, the combination of these Master variables can be analyzed for the advection, dispersion, adsorption, diffusion, and decay processes commonly used in the evaluation of hydrobiogeochemical transport and fate.

We view environmental systems (in a continental setting) as including six interrelated *subsystems*: 1) Atmosphere (Climate); 2) Surface water; 3) Ground water; 4) Terrestrial ecosystem; 5) Aquatic ecosystem; and 6) Socioeconomic. Each subsystem, in turn, consists of a set of spatially distinct *components*. For example, the ground-water system would have two *components*: the unsaturated zone and the saturated zone. We identify environmental *functions*

at the component level of our hierarchy, and define a function as a physical, hydrobiogeochemical or other action that affects the spatial distribution, timing or magnitude of a master environmental variable. Note that a component does not need to be spatially continuous. For example, a watershed surface includes many hillsides that typically are discontinuous. Nevertheless, all hillsides provide similar functions within the overall environmental system. Therefore, all hillsides serve as a single component of the surface water subsystem.

We then define the component *structure* as those environmental processes that describe and control the function. With this definition, component structure includes not only the conceptual and mathematical representation of an environmental process but also the spatial and temporal distribution pattern of system parameters. For example, three-dimensional hydrogeologic geometry may be represented by geometric measurements (thickness, spatial distribution) and media characteristics (hydraulic conductivity, specific yield, porosity) that change in both time and space.

In the environmental systems that we intend to investigate, water is the common thread needed to understand relationships among the subsystems and components. Mass and energy transfer between and storage within components is directly linked to the movement and storage of water.

The general system components include climate (with respect to water), topography, soils (with respect to water), vegetation (with respect to water), surface water, geomorphology, people (with respect to water), geology (structure and lithology), and ground water. These system components are used to characterize the surface water and ground-water systems (Figure 1), which, in turn, is used to characterize the terrestrial and aquatic ecosystems. Finally, the human system (socioeconomic activity) is evaluated to complete the sustainability assessment.

Currently, we are investigating the approach and tools needed to complete the physical and hydrobiogeochemical aspects of a hydrologic system analysis (Figure 2). The logic diagram pertaining to ground-water flow systems has been researched (Kolm, 1996) and several case histories illustrate the applicability of this approach to ground-water flow systems on both the site and ground-water basin scale (for example, San Juan and Kolm, 1996; Talbot and Kolm, 1996), to unsaturated zone hydrology (van der Heijde et. al., 1997), and to wetlands (Harper-Arabie and Kolm, 1998). We are currently researching the applicability of the approach to the physical and hydrobiogeochemical aspects of surface water systems and wetlands.

FUTURE RESEARCH AND DEVELOPMENT

There are three major research “thrusts” that are envisioned. The development and application of this integrated approach needs to continue with respect to watershed, ground-water basin, and wetland scale hydrologic system analysis. These studies will focus initially on water flow and quantity, and water quality. The emphasis will shift to support ecosystem and human system analysis as the appropriate research teams develop.

The second major research area is ecosystem analysis and ecosystem components with an emphasis on water resources as the link. This analysis would include the structure and function of microbial communities, aquatic communities, terrestrial communities, and ultimately landscapes from an ecosystem perspective.

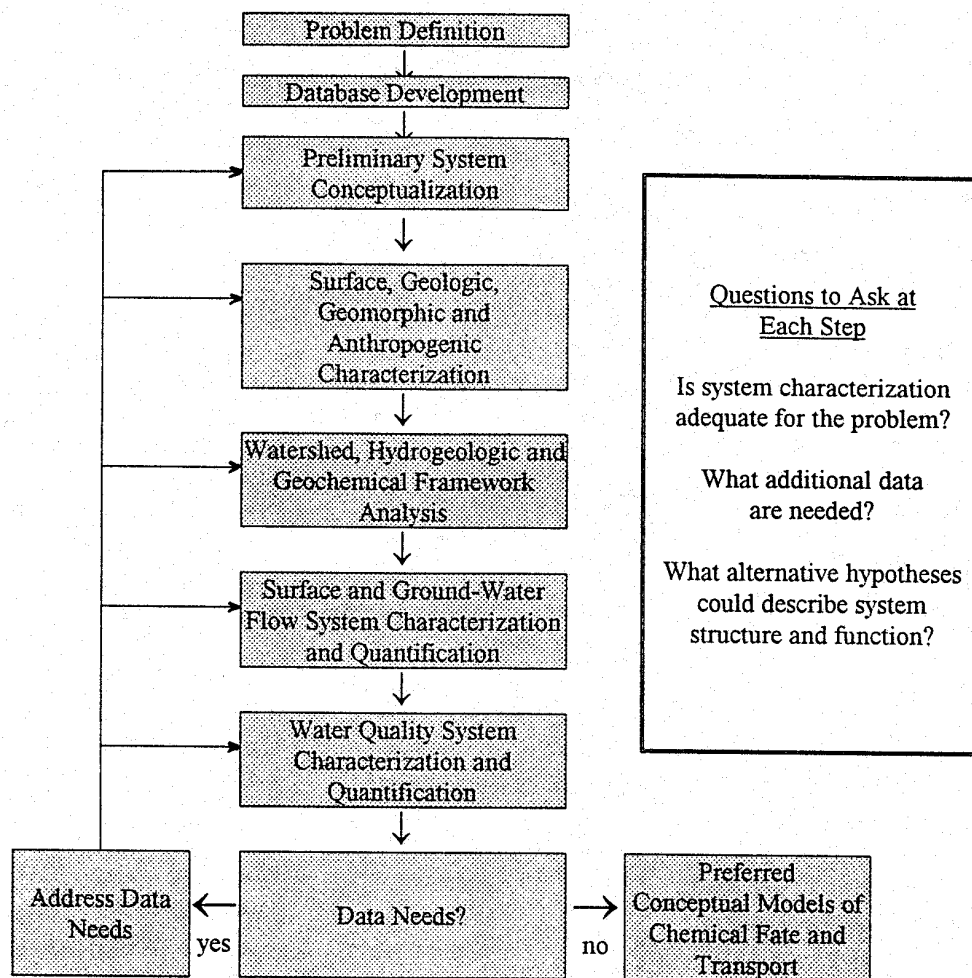


FIGURE 1 Logic Diagram of Hydrologic System Analysis

The final major research area is the human system components with regard to sustainability. The approach would embrace socioeconomics as well as risk assessment and management, and would integrate all of the other components that comprise the natural system into the socioeconomic solutions.

CONCLUSION

In conclusion, we perceive that there is a critical need for quantifying and measuring sustainability of ecosystems, including human components, on a system scale. In order for that need to be met, a multidisciplinary, team- oriented approach will be needed. We envision that the best approach will be to develop integrated technical approaches and tools to characterize ecosystem, and thus, human sustainability from the watershed, ground-water basin, and wetlands perspective and scales using a hierarchical algorithm with nonlinear feedbacks. To achieve our goals, the general system components will consist of layers of information and processes

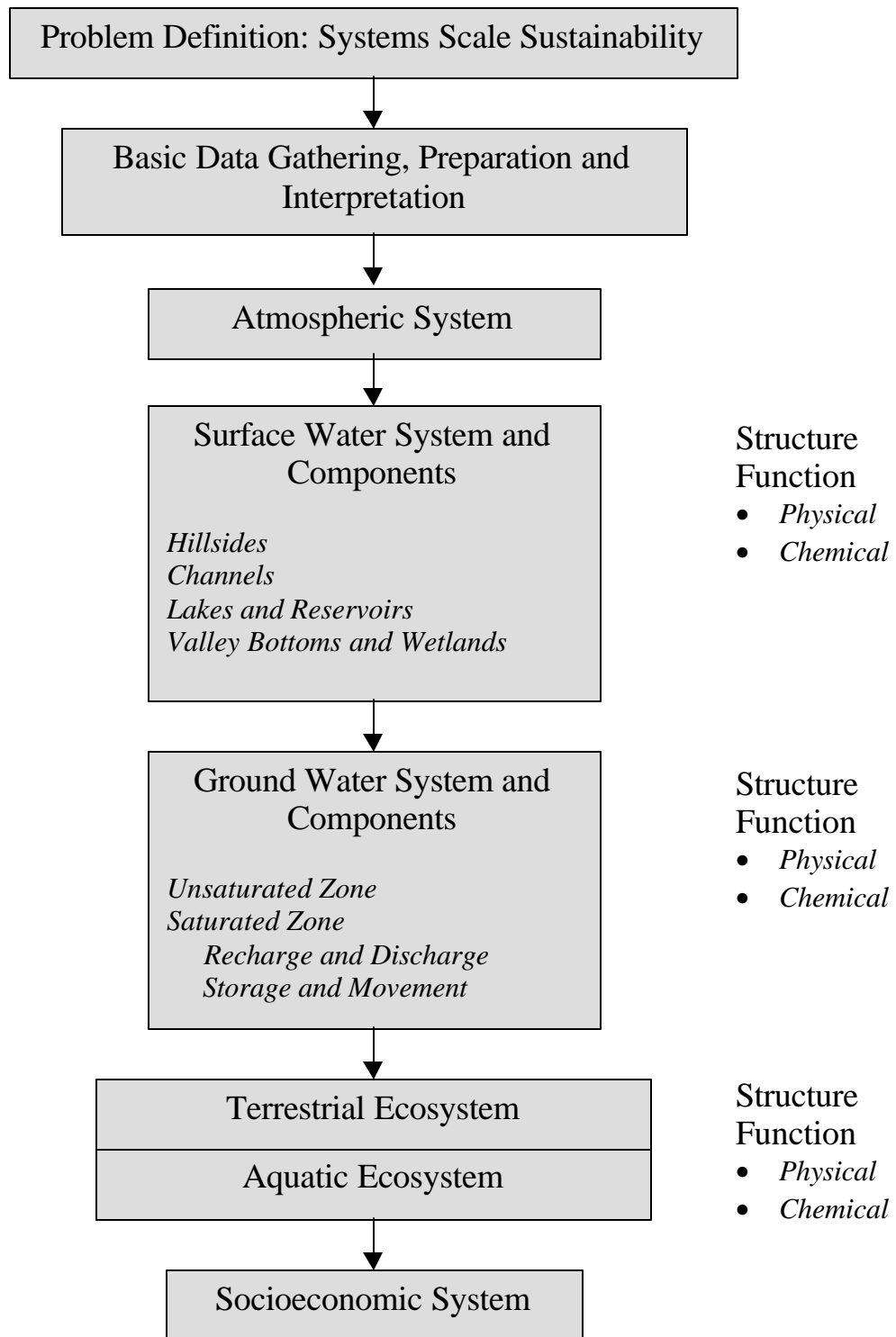


FIGURE 2 Logic Diagram for Characterizing Ecosystem Sustainability

integrated by GIS or other data management and visualization tools, based on engineering, hydrogeological, ecological, and socioeconomic principles.

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ASTM STANDARDS CITED

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